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Greenhouse gas sequestration: downhole seismic monitoring of the Weyburn CO_2 Monitoring Project, Saskatchewan

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Abstract: The International Energy Agency Weyburn CO_2 Monitoring Project has been established as a test site for evaluating a currently producing oil reservoir for point-source CO_2 disposal. Nine-component, three-dimensional vertical seismic profiles will be acquired in three successive years in an attempt to provide time-lapse images of reservoir evolution during the CO_2 flood. The objectives of the downhole seismic study are to characterize the spatial and temporal variations in the physical properties of the reservoir rocks/fluids and surrounding rocks including 1) bulk rock/fluid properties, 2) fluid state and distribution, 3) rock matrix porosity and directional permeability, and 4) controlling fault structures.

Résumé : Dans le cadre de son Projet de surveillance du CO_2 de Weyburn, l'Agence international de l'énergie a établi un site d'essai pour l'évaluation de la capacité de stockage de CO_2 d'une roche réservoir pétrolifère actuellement en exploitation. Durant trois années consécutives, on établira des profils sismiques verticaux tridimensionnels à neuf composants, afin de produire des images par intervalles de l'évolution de la roche réservoir pendant l'injection de CO_2. L'étude sismique de fond a pour objet de caractériser les variations spatiales et temporelles des propriétés physiques des fluides, de la roche réservoir et des roches environnantes, y compris (1) les propriétés apparentes des roches et des fluides, (2) la répartition et l'état des fluides, (3) la porosité matricielle et la perméabilité directionnelle de la roche, et (4) les structures de faille de contrôle.

INTRODUCTION

Reduced emission and disposal of man-made 'greenhouse' gases is currently a topic of interest worldwide. Geological reservoirs have recently been proposed as potential reservoirs for the disposal and long-term storage of the most common greenhouse gas, CO_2. The Weyburn CO_2 Monitoring Project has been established as a test site (Fig. 1) for the purpose of rigorously evaluating a currently producing oil reservoir for point-source CO_2 disposal. This is a collaborative project involving the International Energy Agency, the Reservoir Characterization Project (Colorado School of Mines), Pan Canadian Petroleum, the Petroleum Technology and Research Centre, and Natural Resources Canada. The objective of seismic monitoring is to measure the three-dimensional physical properties of the reservoir and surrounding rocks before, during, and after CO_2 flooding. This will allow assessment of the efficacy of hydrocarbon reservoirs for long-term CO_2 storage.

Carbon dioxide (CO_2) is the primary anthropogenic greenhouse gas and is an important element in models of global climate change. The energy sector has been the major source of anthropogenic CO_2, with the combustion of fossil fuels accounting for 84% to 92% of commercial energy use in western countries. The International Energy Agency estimates that approximately 6 Gt of carbon enter the environment annually as a result of global energy-related CO_2 emissions, with North America being responsible for approximately 20% to 25% of this total. Recognition of the importance of CO_2 emissions has stimulated research toward mitigation of CO_2 effects as mandated under the *Kyoto Protocol* of the United Nations Framework Convention on Climate Change.

Sequestration of CO_2 in geological reservoirs is being evaluated internationally as a viable means of long-term CO_2 storage and climate-change mitigation (European Association of Geoscientists and Engineers, 2000). Canada has stepped to the forefront of promoting research in this area with the establishment of the International Energy Agency (IEA) Weyburn CO_2 Monitoring Project (Government of Canada, *IEA Weyburn CO_2 Monitoring Project Gets Funding*, July 13, 2000 press release, available at http://www.nrcan.gc.ca/css/imb/hqlib/200061e.htm, accessed June 2002.). This project represents one of only two

Figure 1. Location of the Weyburn field in the Williston Basin of southeastern Saskatchewan.

such projects worldwide, the other being the Sleipner project in Norway where CO_2 is disposed of into a deep saline aquifer. Pan Canadian Petroleum is using CO_2 injection as an economic means of increasing the efficiency of oil recovery near Weyburn, in southern Saskatchewan, where CO_2 is being injected into the oil reservoir at a rate of 5000 t/day. Pan Canadian Petroleum estimates that the injection will reduce its CO_2 emissions by 350 billion cubic feet. The purpose of the Weyburn Monitoring Project is to evaluate oil reservoir CO_2 sequestration as a technology for the abatement and/or mitigation of greenhouse gas emissions.

THE SEISMIC MONITORING PROGRAM

Geophysical monitoring is a central element of the proposed multidisciplinary Weyburn CO_2 Monitoring Project. The variety of seismic methods (crossborehole tomography, reverse vertical seismic profiles, three-dimensional time-lapse seismic reflection) used in this study is designed to determine the properties of the reservoir prior to CO_2 flooding and subsequently to study the evolution of the reservoir during the injection process (e.g. Talley et al., 1998). Toward this end, the GSC is participating with the lead organizations, Colorado School of Mines and Lawrence Berkley National Laboratory, with support from the Petroleum Technology and Research Centre and Pan Canadian Petroleum. Specifically, the GSC is focusing on the use of downhole seismic recording as a means of complementing the surface three-dimensional seismic data. The objectives of the downhole seismic study are to characterize the spatial and temporal variations in the physical properties of the reservoir rocks/fluids and surrounding rocks during progressive stages of the CO_2 flooding process, including 1) bulk rock/fluid properties, 2) fluid state and distribution, 3) rock matrix porosity and directional permeability, and 4) controlling fault structures.

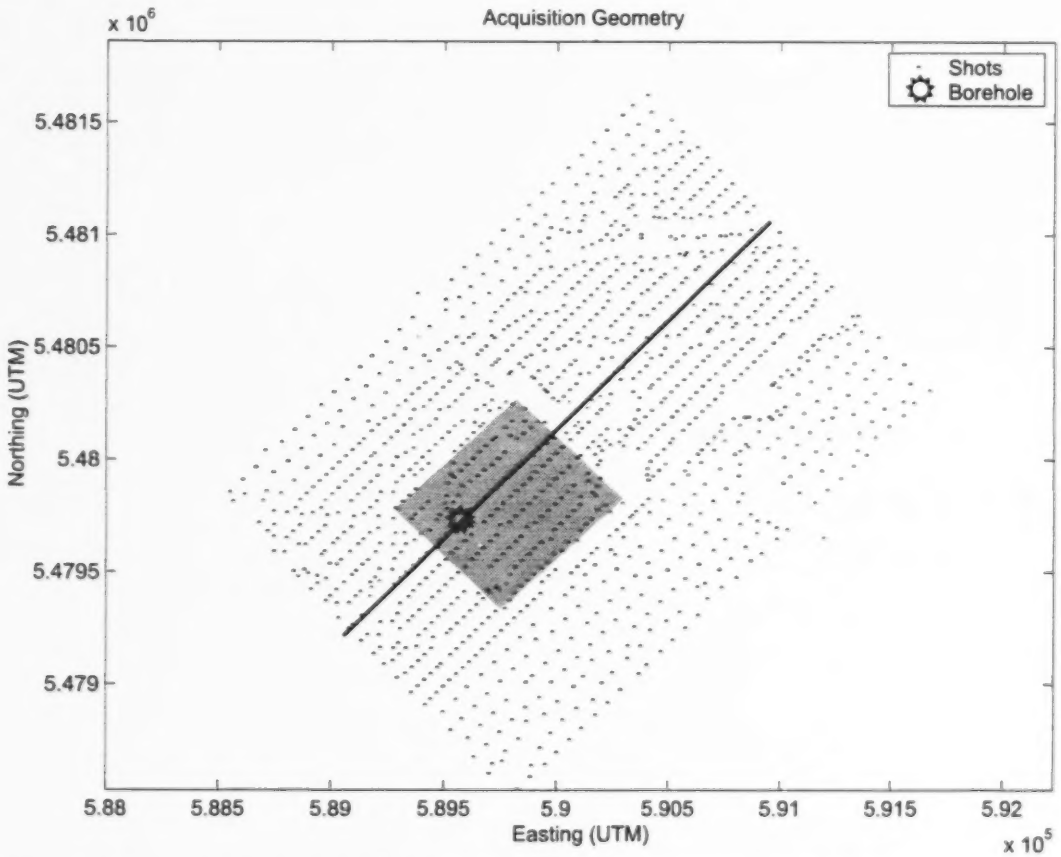

Figure 2. *Acquisition geometry map showing three-component source points from the Phase II survey and the borehole location. The shaded area is the subregion to be imaged at reservoir depth using the three-dimensional vertical seismic profile data. The solid line indicates the source line for the receiver gather shown in Figure 5.*

The potential advantages to downhole recording of the surface excited data include a higher prestack S/N ratio due to avoidance of the near-surface layer, potentially allowing more extensive prestack analysis, the partial removal of seasonal near-surface variations that compromise time-lapse images, and improved subsurface resolution due to preservation of a broader frequency bandwidth signal. A comparison of the various monitoring methods will provide direction for establishing robust monitoring methods and standards for CO_2 sequestration reservoirs.

Data acquisition

Surface three-dimensional, nine-component seismic surveys were conducted over an area approximately 2 km by 3 km (Fig. 2) above the reservoir at the onset of CO_2 flooding in the fall of 2000 (Phase I) and one year later in the fall of 2001 (Phase II). A third survey (Phase III) is planned for the fall of 2002. A multilevel, three-component downhole recording system (Fig. 3) was deployed during each of the first two surface three-dimensional surveys, to record energy from the three-component surface source (Fig. 4) as it vibrates over a grid of points during the surface three-dimensional survey. A data example from one level of the tool is shown in Figure 5. A third deployment of the downhole system is planned for the Phase III, three-dimensional, nine-component survey. In total, 3 three-dimensional, nine-component downhole data sets will be acquired that can be used to form time-lapse images. The downhole multilevel tool was deployed at two depth intervals, i.e. twelve levels (at 15 m intervals) directly above the reservoir (at about 1400 m) and four levels at about 900 m. The deeper set of levels was designed to provide waveform control for processing the surface three-dimensional data set, whereas the shallower set of geophones was placed to allow low-fold reflection imaging of a three-dimensional volume that has a plan view area of approximately 1/4 by 1/4 of the surface survey size.

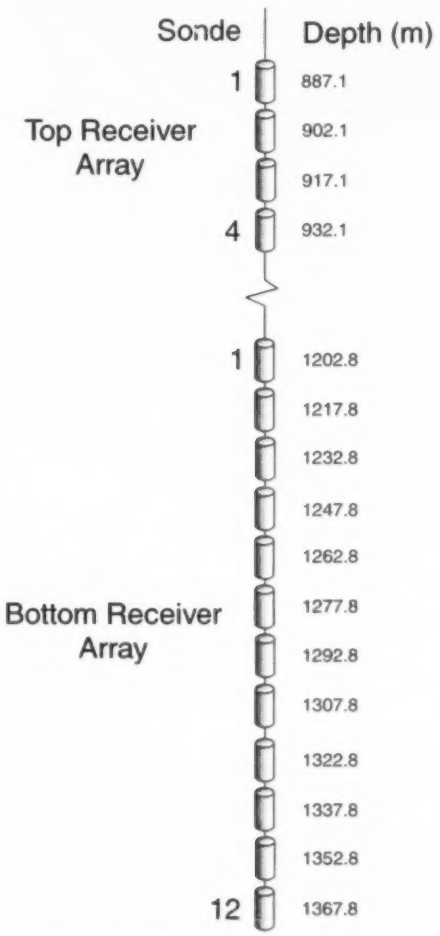

Figure 3. *Recording geometry of the 16-level, 3-component downhole system.*

Data processing and analysis of the downhole data

Planned processing and analysis of the nine-component, three-dimensional vertical seismic profile data includes the following. 1) Process to obtain a three-dimensional volume beneath the borehole tool depth, for P-wave and S-wave data. 2) Produce a three-dimensional volume for P-S wave conversions for comparison of processing methods. 3) Calculate static and time-lapse images of interval velocities and other seismic attributes for the reservoir and surrounding zone. 4) Compare interval travel times for different phases to obtain anisotropy estimates in the vicinity of the reservoir, and compare with anisotropy determined from initial and follow-up three-dimensional surface survey. 5) Undertake polarization analysis to map the spatial variation in anisotropy of the reservoir and surrounding zone, by applying a 'layer-stripping' approach. 6) Undertake fault imaging; use some of the imaging methods developed for steep geology in mining-camp studies to try and image fault zones directly.

This analysis will allow 1) monitoring of bulk seismic properties that track CO_2 flooding of the reservoir; 2) production of high-resolution, time-lapse images of seismic attributes to track changes in lithology and pore fluids within the reservoir during and/or after injection; 3) assessment of CO_2-reservoir fluid interaction and displacement from the interpretation of seismic images; and 4) evaluation of the suitability of downhole seismic methods for monitoring injection effects.

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Brian Roberts provided field supervision during Phase II data acquisition and a critical review of a draft version of this article.

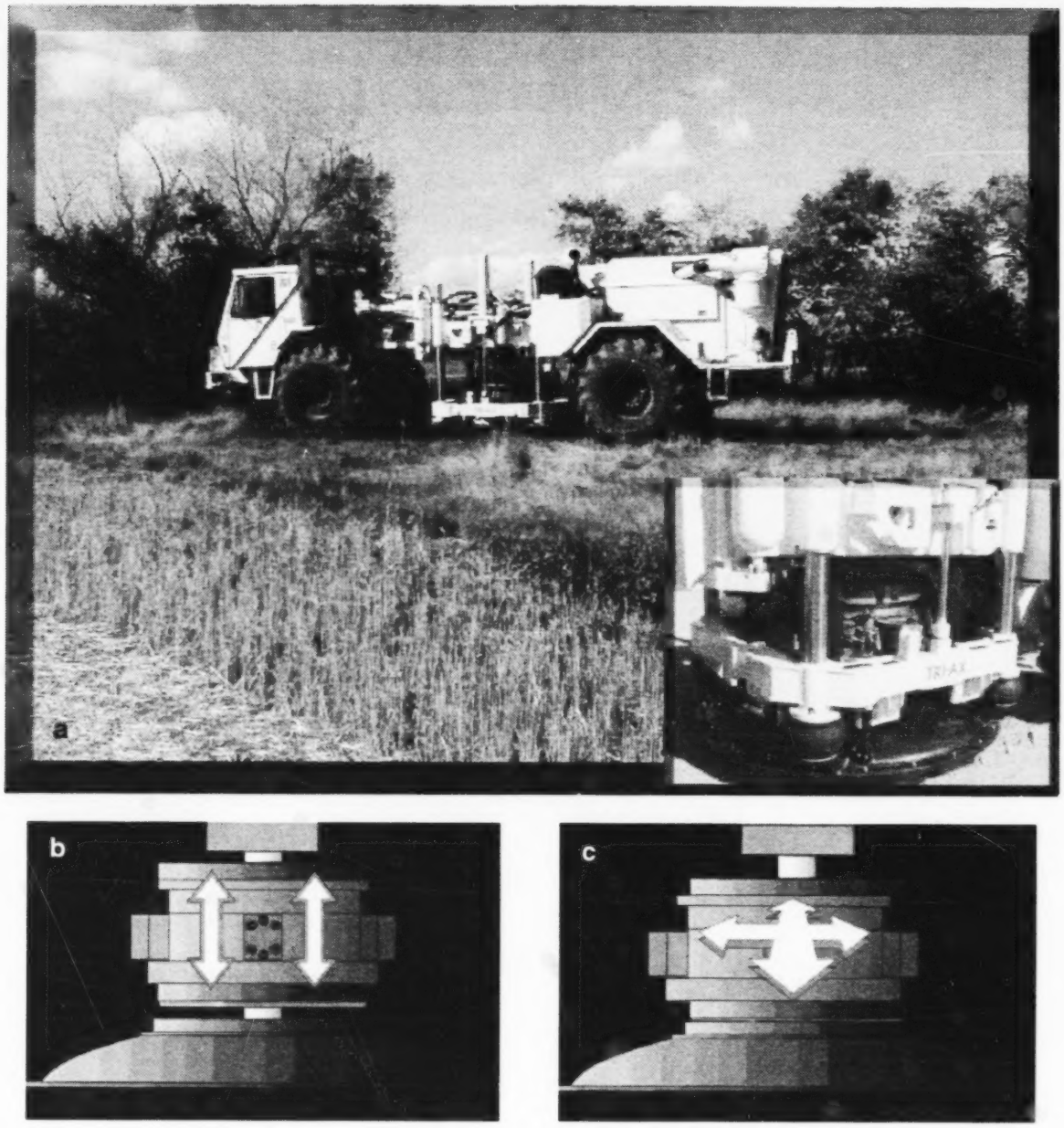

Figure 4. ***a****) IVI Triaxial Vibrator truck that provided the three-component source for the seismic survey. Inset shows a close-up of the vibrating mechanism. Schematics of vibrating mass for vertical* ***b****) and two horizontal (****c****: in-line and crossline) modes of wave generation.*

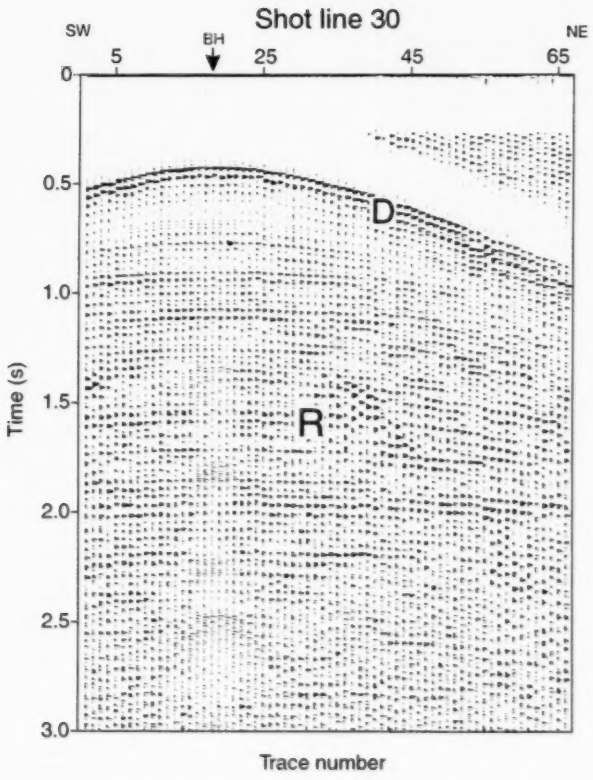

Figure 5. *Vertical component, common receiver gather for a line of P-wave shots across the surface location of the borehole. D is the direct arrival and R is the reflection from the reservoir interval.*

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